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6. AUTHOR(S)
S. James Allen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Santa Barbara
Quantum Institute
Santa Barbara, CA 93106

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13. ABSTRACT (*Maximum 200 words*)

Non-linear electron dynamics in semiconductor quantum structures define a rich scientific arena with potential impact on novel devices in the terahertz regime. An important concept is photon assisted transport, marked by new transport channels, opened by the absorption or emission of one or more photons. Experiments carried out during this project have exposed several phenomena, new to semiconductor quantum devices, antenna coupled to intense terahertz electric fields: 1) Multiple photon assisted tunneling, accompanied by both stimulated emission and absorption of up to three terahertz photons. 2) Electric field domains supported by multi-photon assisted sequential resonant tunneling. 3) Terahertz driven dynamic localization and absolute negative resistance. 4) A classical / quantum crossover frequency. 5) Multi-photon resonances with Bloch oscillation in electrically biased miniband superlattices. These experiments have opened the arena of photon assisted transport to semiconductor devices and paved the way for future terahertz electronics based on quantum transport in semiconductor nano-structures.

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Title: "High Electric Field Quantum Transport: Submillimeter wave AC Stark Localization in Vertical and Lateral Superlattices"

PI: S. James Allen
UC Santa Barbara

Period: 04/01/93 - 03/31/96

Non-linear electron dynamics in semiconductor quantum structures define a rich scientific arena with potential impact on novel devices in the terahertz regime. An important concept is photon assisted transport, marked by new transport channels, opened by the absorption or emission of one or more photons. Recent experiments carried out by us have exposed, in a graphic way, several phenomena related to photon assisted tunneling in multi-quantum well superlattices, antenna coupled to intense terahertz electric fields.

- Photon assisted tunneling in double quantum well / triple barrier resonant tunneling diodes reveals ***multiple photon assisted tunneling***, accompanied by both emission and absorption of up to three terahertz photons.

- ***Multi-photon assisted*** sequential resonant tunneling is observed in superlattices driven by terahertz fields. Electric field domains are supported by these photon assisted channels.

- Terahertz driven sequential resonant tunneling superlattices have exposed ***dynamic localization*** for the first time. Remarkably, dynamic localization is accompanied by ***absolute negative resistance***.

- ***Stimulated photon emission*** as well as absorption channels are recovered near zero bias.

- Delineated the ***classical / quantum crossover frequency*** in these systems.

- Multi-photon ***resonances with Bloch oscillation*** are observed in electrically biased miniband superlattices.

Elements of the experimental approach that contributed to its success are the following:

- Integration of micron size test structures into "bow tie" antennas.

  Antenna coupling enhanced the terahertz electric field impressed on the device and assured that the electric field inside the quantum well structure was reasonably uniform. Collaboration with graduate student researcher U. Bhattacharya and Dr. M. Rodwell in Electrical and Computer Engineering at UCSB is gratefully acknowledged.

- "Tailor made" quantum well structures grown by MBE.

  Strong quantum confinement in vertical structures allows photon assisted processes to persist to 100's K. Collaboration with graduate student researchers Ken Campman,

Kevin Maranowski, D. Leonard and G. Madeiros-Ribeiro and Dr. A.C. Gossard in the Materials Department at UCSB is gratefully acknowledged.

- Intense tunable radiation form the UCSB Free-electron Lasers.

The UCSB FEL's provide kilowatts of tunable radiation from 120 GHz to 4.8 THz. Terahertz field strengths of the order of kilovolts/cm lift these test structures into the non-perturbative limit.

Triple barrier / double quantum well resonant tunneling diodes. It has been difficult, if not impossible, to recover photon assisted tunneling features due to "quantum rectification" in a simple resonant tunneling diode. Empirically this is due to the fact that the resonant tunneling features are very broad even when the voltage is properly scaled to the photon energy. **2D - 2D tunneling** is marked by relatively sharp features in the I-V. (Fig. 1.) Here, clear photon assisted tunneling in the quantum rectified response persists to temperatures above 200 K.

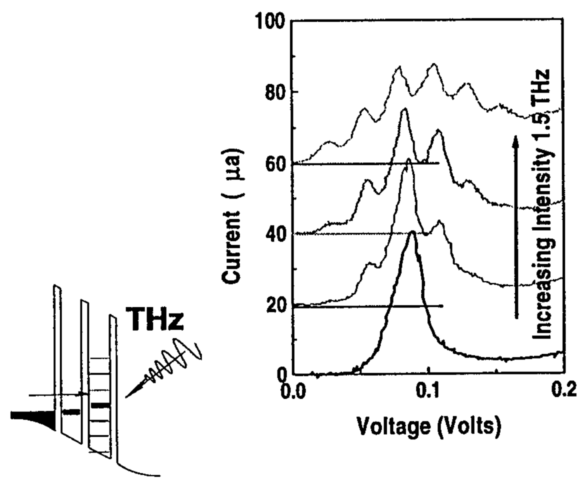

Fig. 1 2-D to 2-D tunneling in a double quantum well resonant tunneling diode displays sharp photon assisted features at terahertz frequencies.

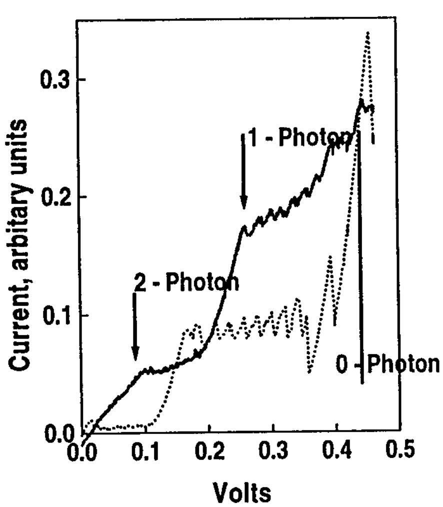

Fig. 2 Current voltage characteristic without and with radiation at 3.42 THz .

Multiphoton sequential resonant tunneling. Sequential resonant tunneling is characterized by extremely non-linear current voltage characteristics. It is marked by major steps in current when the applied field uniformly aligns the superlattice such that the ground state in the "up hill" well is resonant with the excited state in the "down hill" well. Smaller features appear between these major steps that signal the motion of an electric field domain across the sample. (Fig. 2) In the presence of intense terahertz radiation, new steps appear that signal the appearance of photon assisted sequential resonant tunneling and electric field domains.

For small DC voltages the current flows by means of ground state to ground state tunneling. There is a maximum current that can flow: above that, electric field domains form. The conductance at zero volts is suppressed by the terahertz field, a manifestation of ***dynamic localization***. Remarkably, the conductance is driven through zero and ***absolute negative conductance*** appears. (Fig. 3) When the electrons in the superlattice are dynamically localized, they **flow "up-hill"**.

Accompanying the dynamic localization, multiphoton assisted tunneling by ***stimulated emission*** appears. These are "gain" channels for frequencies less than the Stark splitting. (Fig. 3)

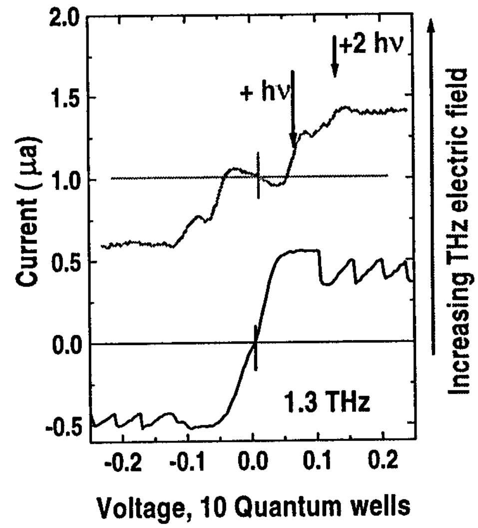

Fig. 3 Current voltage characteristic of a superlattice exhibiting dynamic localization and absolute negative conductance.

Bloch Oscillation. By reducing the barrier thickness, the sequential resonant tunneling superlattice evolves into a miniband superlattice with coherent transport over several superlattice quantum wells, ≈10 in the case we explored, (2nm barriers of $Al_{.3}Ga_{.7}As$ and 8 nm GaAs quantum wells). High electric field transport is now controlled by ***Bloch oscillation***. When irradiated with terahertz radiation, sharp discontinuities appear in the current, at voltages that scale with the frequency. (Fig. 4) These appear to be single and multi-photon resonances with Bloch oscillation. This is an analog of Shapiro steps in irradiated superconductor junctions due to the AC Josephson effect.

All of these phenomena are semiconductor analogs of photon assisted processes that are normally only seen in superconducting junctions, such as, photon assisted quasi-particle tunneling and the AC Josephson effect. These experiments have opened the rich arena of superconducting electronics, to semiconductor electronics.

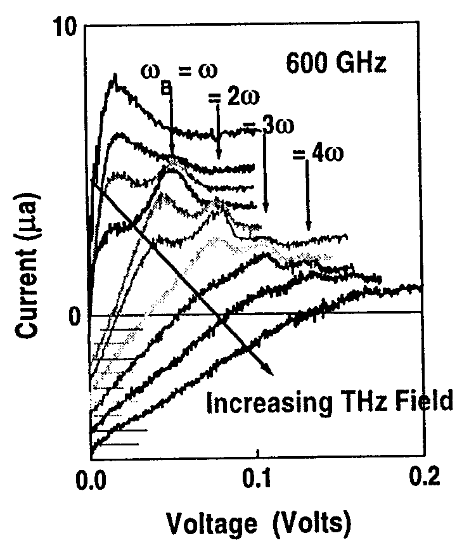

Fig. 4 Multi photon resonance with Bloch oscillation in a miniband superlattice.

In keeping with the character of the terahertz regime, as a transition region between electronics and photonics, these phenomena are a mix of transport and quantum processes in

terahertz fields. This research has underscored **the potential of semiconductor quantum structures to make possible terahertz electronics.**

Patent Disclosure:

"A method for fabricating photonic-band-gap structures", Inventor: M.C. Wanke, UC Case No. 95-305-1.

Publications:

K. Unterrainer, B.J. Keay, M.C. Wanke, S.J. Allen, D. Leonard, G. Madeiros-Ribeiro, U. Bhattacharya, M.J.W. Rodwell, "Inverse Bloch Oscillator: Strong terahertz-photocurrent resonances at the Bloch frequency", Phys. Rev. Lett. **76**, 2973 (1996).

S. Zeuner, B.J. Keay, S.J. Allen, K.D. Maranowski, A.C. Gossard, U. Bhattacharya and M.J.W. Rodwell, "Transition from classical to quantum response in semiconductor superlattices at THz frequencies", Phys. Rev. B, Rapid Commun., **53**, R1717 (1996).

Keay, B.J., Allen, S.J., Jr., Galan, J., Kaminki, J.P., et al.., "Photon-assisted electric field domains and multiphoton-assisted tunneling in semiconductor superlattices." Phys. Rev. Lett., **75**, 4098 (1995).

Keay, B.J., Zeuner, S., Allen, S.J., Jr., Maranowski, K.D., et al.., "Dynamic localization, absolute negative conductance, and stimulated, multiphoton emission in sequential resonant tunneling semiconductor superlattices." Phys. Rev. Lett., **75**, 4102 (1995).

Allen, S.J., Craig, K., Galdrikian, B., Heyman, J.N., et al.. "Materials science in the far-IR with electrostatic based FELs." Nucl. Instr. & Meth. in Phys. Res., **A358**, 536 (1995).

Drexler, H., Scott, J.S., Allen, S.J., Campman, K.L. and Gossard, A.C., "Photon-assisted tunneling in a resonant tunneling diode: Stimulated emission and absorption in the THz range.", Appl. Phys. Lett., **67**, 2816 (1995).

Allen, S.J., Craig, K., Felix, C.L., Guimaraes, P., et al.. "Probing tetrahertz dynamics in semiconductor nanostructures with the UCSB free-electron lasers.", J. of Lumin., **60-61**, 250 (1994).

Allen, S.J., Keay, B.J., Guimaraes, P.S.S., Kaminski, J.P., Hopkins, P.F. and Gossard, A.C., "Terahertz, photon assisted tunneling in semiconductor nanostructures.", in <u>Nanostructures and Quantum Effects</u>, edited by H. Sakaki and H. Noge, Springer-Verlag, Berlin, 1994, pp. 133-139.

Keay, B.J., Guimaraes, P.S.S., Kaminski, J.P., Allen, S.J., Jr., et al.. "Superlattice transport in intense terahertz electric fields." , Surf. Sci., **305**, 385 (1994).

Kaminski, J.P., Allen, S.J., Sherwin, M., Keay, B., et al.., "Probing terahertz electron dynamics in semiconductor nanostructures with the UC Santa Barbara FELs.", Nuc. Instr. & Meth. in Phys. Res., **A341**, 169 (1994).

Guimaraes, P.S.S., Keay, B.J., Kaminski, J.P., Allen, S.J., Jr., et al.. "Electrical transport properties of superlattices under intense terahertz electric fields. Brazil. J. Phys., **24**, 163 (1994)

Guimaraes, P.S.S., Keay, B.J., Kaminiski, J.P., Allen, S.J., Jr., et al. "Photon-mediated sequential resonant tunneling in intense terahertz electric fields.", Phys. Rev. Lett., **70**, 3792 (1993).

Human Resource Development (Supported or affiliated with this project.)

Graduate student researchers:

Brian Keay, Ph.D. in Physics December 1995.

Mike Wanke, Ph. D. candidate.

Post-doctoral researchers supported by fellowship but working on this project:

Karl Unterrainer Jan. 1994 - August 1995

Stefan Zeuner Jan. 1995 - present

Post-doctoral researcher partially supported by this project.

Hermann Drexler November 1994 - March 1996.

Undergraduate researchers

Gerhard Kminet, Sept. 94- June 95